Global Atmospheric Turbulence Decision Support System for Aviation

NASA ROSES-2007: Decision Support through Earth Science Research Results
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Progress Report for Year 1, covering April 10, 2008 – March 15, 2009

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This report summarizes work accomplished between the grant inception and March 15, 2009, comprising roughly the first 11 months of the period of performance. A summary of work performed and milestones completed during this period is summarized below, organized by tasks as listed in the proposal. These accomplishments reflect the combined efforts of the project team, consisting of scientists and engineers at the University of Wisconsin, Madison (UW) Space Science and Engineering Center (SSEC) Cooperative Institute for Meteorological Satellite Studies (CIMSS) and UCAR's National Center for Atmospheric Research (NCAR) Research Applications Laboratory (RAL).

General Information

The first-year award funding increment of $304k was received at UCAR on approximately June 9, 2008, and the subaward between UCAR and the UW-Madison SSEC was completed on October 1, 2008. A science team kickoff meeting was held on June 11, 2008 at NCAR. Teleconferences were held on July 15, September 16, October 1, November 11, and December 16, 2008 and February 10 and March 10, 2009, and most of the project team met in person at the SPIE conference on August 14, 2008 and at the AMS Annual Meeting on January 14, 2009.

The principal Year 1 milestones and target dates are listed under each task, as is the estimated percent completion (relative to the 3-year project goals) of each task. In summary, 12 of the 17 Year 1 milestones have already been completed as scheduled, and the remaining 5 are on track to be completed on time and within budget. Progress has already been made on some Year 2 tasks as well, including visualization of real-time data. No major problems have been encountered.

Metrics summary:

Percent of milestones met on time: 100% (12 of 12)
Percentage of past reports submitted on time: 100% (2 of 2)
Number of conference and journal articles submitted: 1
Number of conference presentations: 3
Duration of identified problems that have not been solved: NA

Conference papers:

Williams, J. K., R. D. Sharman, C. J. Kessinger, W. Feltz, A. Wimmers, and K. Bedka, 2009: Developing a global atmospheric turbulence decision support system for aviation. AMS 7th Conference on Artificial Intelligence and its Applications to the Environmental Sciences, oral presentation 2.4.

Conference presentations:

Bedka, K. M., J. C. Brunner, W. F. Feltz, and R. Dworak, 2009: Development of objective overshooting top and enhanced-V detection algorithms for GOES-R ABI. *AMS 16th Conference on Satellite Meteorology and Oceanography*. Phoenix, AZ, poster presentation JP7.5. (co-sponsored)

Williams, J. K., R. D. Sharman, C. J. Kessinger, W. Feltz, A. Wimmers, and K. Bedka, 2009: Developing a global atmospheric turbulence decision support system for aviation. *AMS 7th Conference on Artificial Intelligence and its Applications to the Environmental Sciences*, oral presentation 2.4.

Wimmers, A. and W. Feltz, 2009: Nowcasting aircraft turbulence from tropopause folds operationally for GOES-R. *AMS 16th Conference on Satellite Meteorology and Oceanography*. Phoenix, AZ, poster presentation JP7.17. (co-sponsored)

Budget vs. Actual Expenditures for UCAR/NCAR, Year 1

	Budgeted	Actual	Cum. Budget	Cum. Actual
Q1 (Apr-Jun 2008):	10,000	5,804	10,000	5,804
Q2 (Jul-Sep 2008):	10,000	11,791	20,000	17,594
Q3 (Oct-Dec 2008):	85,000	80,307	105,000	97,901
Q4 (Jan-Mar 2009):	90,000	56,119 *	195,000	136,426 *
Q5 (Apr 1-9, 2009):	10,175	NA	205,175	NA

* *As of February 28, 2009*

Note: An additional $85,500 for the UW-Madison subcontract and $13,325 for UCAR overhead on the subcontract were placed in a separate UCAR account for disbursement as UW-Madison invoices are received and are not included in the amounts above. UCAR's Q1 and Q2 budget and spending were relatively low due to the time required for funding to arrive (2 months after the project start), for the needed hardware purchase and setup and for project staff to complete FY08 obligations on other projects. However, the Year 1 allocation for UCAR will be completely spent by April 10, 2009.

Budget vs. Actual Expenditures for UW-Madison SSEC/CIMSS, Year 1

	Budgeted	Actual	Cum. Budget	Cum.. Actual
Q1 (Apr-Jun 2008):	10,000	0	10,000	0 †
Q2 (Jul-Sep 2008):	10,000	0	20,000	0 †
Q3 (Oct-Dec 2008):	30,000	19,698	50,000	19,698
Q4 (Jan-Mar 2009):	30,000	30,000 (est) *	80,000	49,698 (est) *
Q5 (Apr 1-9, 2009):	5,500	NA	85,500	NA

[†] *Contract not yet in place*
[*] *As of February 28, 2009*

Note: UW-Madison spending has been slower than anticipated since the UCAR/UW-Madison subcontract was not in place until October 2008 (nearly 6 months after the project start). UW-Madison spending has now accelerated and it is estimated that the remaining Year 1 funds will be fully invoiced by May 31, 2009. In Year 2, spending at a more systematic pace is anticipated.

Task 1: Model-based turbulence forecasting

Percent completion: 35%

Year 1 milestones and target dates:

11-28-08 Initial GFS-based diagnostics development and software complete (DONE)

2-26-09 Initial GFS GTG combination algorithm complete (DONE)

4-9-09 Initial GFS GTG software complete and running in real-time (on track to be completed)

Summary of efforts:

Software has been developed to ingest GFS data and compute turbulence diagnostics for use in the global turbulence forecasting system. The diagnostic computations have been modified in three ways from those previously developed for use on CONUS RUC and WRF model data:

1) The boundary conditions have been modified to account for the 0 deg longitude meridian and to correctly handle the regions near the poles.
2) Map projections were developed for what is essentially a Mercator grid, and the singular points at the poles have been accommodated.
3) A single turbulence diagnostics computational core has been developed to support RUC, WRF and GFS model data.

Testing of the GFS-based code has been performed by comparing output to the RUC-based code running over the CONUS and to aircraft turbulence pilot reports and automated measurements (see Figure 1 and Figure 2 in Appendix A). These tests were done on archived GFS data that were downloaded from the NCAR Mass Store System. NCAR staff have worked with Geoff Manikin and John Ward (NOAA) to change the 0.33 degree GFS format from grib1 to grib2. Geoff also added the 3 and 9 hour forecast to the data stream. These data changes have been coordinated with the other institutional users of these data. (See also Task 6.)

An initial GFS GTG combination algorithm has been developed for combining the GFS-based turbulence diagnostics to create a prototype global turbulence product. It makes use of the following turbulence diagnostics: Ellrod1, DTF3, FRNTGth, VWS, SatRi, TEMPG, NVA, NCSU2, EDRS and SIGW. Visualization tools have been developed for viewing the model fields and GFS GTG output, and for overlaying turbulence reports and measurements as well as other data. The initial GFS GTG product is illustrated in Figure 2 – Figure 4 of Appendix A. In addition, a probabilistic version of GFS GTG under development treats the various turbulence diagnostics as members of an ensemble. Prototype probabilistic output is shown in Figure 5.

Task 2: Satellite-based turbulence identification

Percent completion: 25%

Year 1 milestones and target dates:

12-31-08 Initial prototype Tropopause Folding Algorithm complete (DONE)

2-26-09 Initial TFA data delivered to NCAR for analysis (DONE)

4-9-09 Initial TFA evaluations and case studies complete (DONE)

4-9-09 Initial MWT algorithm (wave ID) complete (on track to be completed)

4-9-09 Initial CIT diagnostics algorithm complete (DONE)

Summary of efforts:

The initial prototype Tropopause Folding Algorithm (TFA) has been implemented in Fortran and optimized for speed. The initial TFA software was delivered to NCAR on February 10, 2009. The algorithm is currently going through the initial evaluation phase. The prototype TFA is now able to analyze case studies and produce output from the Fortran code for tropopause fold location, height, and direction of strongest turbulence. Additional detail and results from the TFA may be found in Appendix B.

A new CIT diagnosis based on overshooting tops identified via IR data has been developed under another NASA grant. Evaluation at CIMSS shows that this field holds excellent promise for global application. A parallax adjustment is under development. CIMSS has already provided prototype Overshooting Tops identification software to NCAR, earlier than originally planned, for implementation and incorporation into the Task 7 database. CIMSS will provide retrospective analyses to NCAR for additional comparisons and statistical evaluation in Year 2.

Work has also progressed on development of a mountain wave identification algorithm. Please see Appendix B for more details on these work areas.

Task 3: Global convection nowcasting

Percent completion: 25%

Year 1 milestones and target dates:

12-31-08 Initial prototype CDO product modified for MTSAT and Meteosat complete (DONE)

4-9-09 Initial prototype CDO product software complete and running in real-time (on track to be completed)

4-9-09 Initial CDO evaluation and case studies complete (on track to be completed)

Summary of efforts:

NCAR/RAL has received from CIMMS and ingested the MTSAT, Meteosat7 and Meteosat9 data for the 15th of each month in 2007. These datasets are being used to support the development of modifications to the convective diagnosis oceanic (CDO) product so that it will produce reliable global results. Work has begun on applying parallax correction to the satellite products.

Real-time ingest and processing of GOES full-disk scans continue to run on the project's development server (see also Task 6). An prototype global CDO field, generated without cloud classification input, is being generated in real-time. This field is based on the algorithm for the Gulf of Mexico CDO field and hasn't yet been fully evaluated and tuned by the project scientists. In addition, a research (CIDD) display has been set up for viewing all of the fields being ingested and generated by the convective diagnosis processes. For sample CDO output, please see Appendix C. For comparisons with GFS GTG data, see Appendix A.

Inquiries confirmed that "bent pipe" MODIS data have a time latency of about 1.5 hours unless data is received from direct broadcast. Despite the time lag, these data may be useful, particularly in polar regions.

Task 4: Convective turbulence diagnostics

Percent completion: 0%

Year 1 milestones and target dates:

4-9-09 Initial validation of GFS and CDO data collected for analysis complete (on track to be completed)

Summary of efforts:

None to date.

Task 5: Expert system integrator

Percent completion: 0%

Year 1 milestones and target dates:

No substantive effort on this task is scheduled during Year 1.

Summary of efforts:

None to date.

Task 6: DSS product demonstration and dissemination

Percent completion: 15%

Year 1 milestones and target dates:

7-31-08 NCAR project server purchase, setup and configuration complete (DONE)

10-31-08 Initial real-time satellite data ingest complete (DONE)

12-31-08 Initial GFS model data ingest complete (DONE)

Summary of efforts:

A project server was purchased, set up, and configured for use in assembling a database, algorithm development, and real-time data ingest and system prototyping. The server, gturb1, was set up as a 64-bit Etch Debian Linux system.

- A special administrative account was set up for running the server/client infrastructure software. Unidata's Local Data Manager (LDM) software has also been set up and is running reliably.
- The Terrascan G11 and G12 full disk scans continue to be processed in real-time.
- The GFS 0.33 degree resolution 00, 03, 06, 09, 12, 18, 24 and 36-hour pressure-coordinate files are being ingested in real-time. These replace the 0.5 degree GFS files that were used in the system initially.

- Software to convert GFS data to NetCDF format has been installed.
- A SysView data-flow diagram has been created to document and monitor the system components (see Tasks 1 and 3).

The real-time data ingest and processing needed for product development and prototyping is already straining the capacity of the existing project server. Therefore, additional hardware was ordered in early March, somewhat earlier than originally scheduled (this purchase was originally budgeted for Year 2).

Please see Tasks 1 and 3 for other recent accomplishments related to this task, including the development of a data visualization and comparison capability.

Task 7: Performance evaluation and tuning

Percent completion: 10%

Year 1 milestones and target dates:

12-31-08 (DONE)	Initial DB development and population with turbulence "truth" data complete
2-26-09 (DONE)	Initial population of DB with SIGMETS, GFS, CDO, and TFA data complete

Summary of efforts:

- SIGMET data for 20070119 to 20080731 have been brought down from the NCAR MSS archive and converted into a RAL-specific database format.
- PIREP and AIREP data for 2007 and 2008 have been collected and inserted into the mySQL database.
- AMDAR data for the past 8 years has been collected and the last two years have been inserted into the database.
- GFS analysis data are being downloaded from the NCAR MSS archive starting with 20071117 forward. These are being used to compute turbulence diagnostics and for comparison with the in-situ turbulence data (EDR, U_{de}, and AIREPs); see Figure 3 – Figure 5 in Appendix A.

Appendix A: Further Results from Task 1, Model-based Turbulence Forecasting

As mentioned in the report text, turbulence diagnostics have been developed to run globally on GFS model data. The following figure shows a comparison of three different turbulence indices running on GFS and RUC model data. It can be seen that the Ellrod and EDR turbulence indices show reasonable agreement over the RUC domain, but the Richardson number from thermal wind breaks down at the equator, underscoring the need for the development of regionally-sensitive diagnostic selection and combination logic.

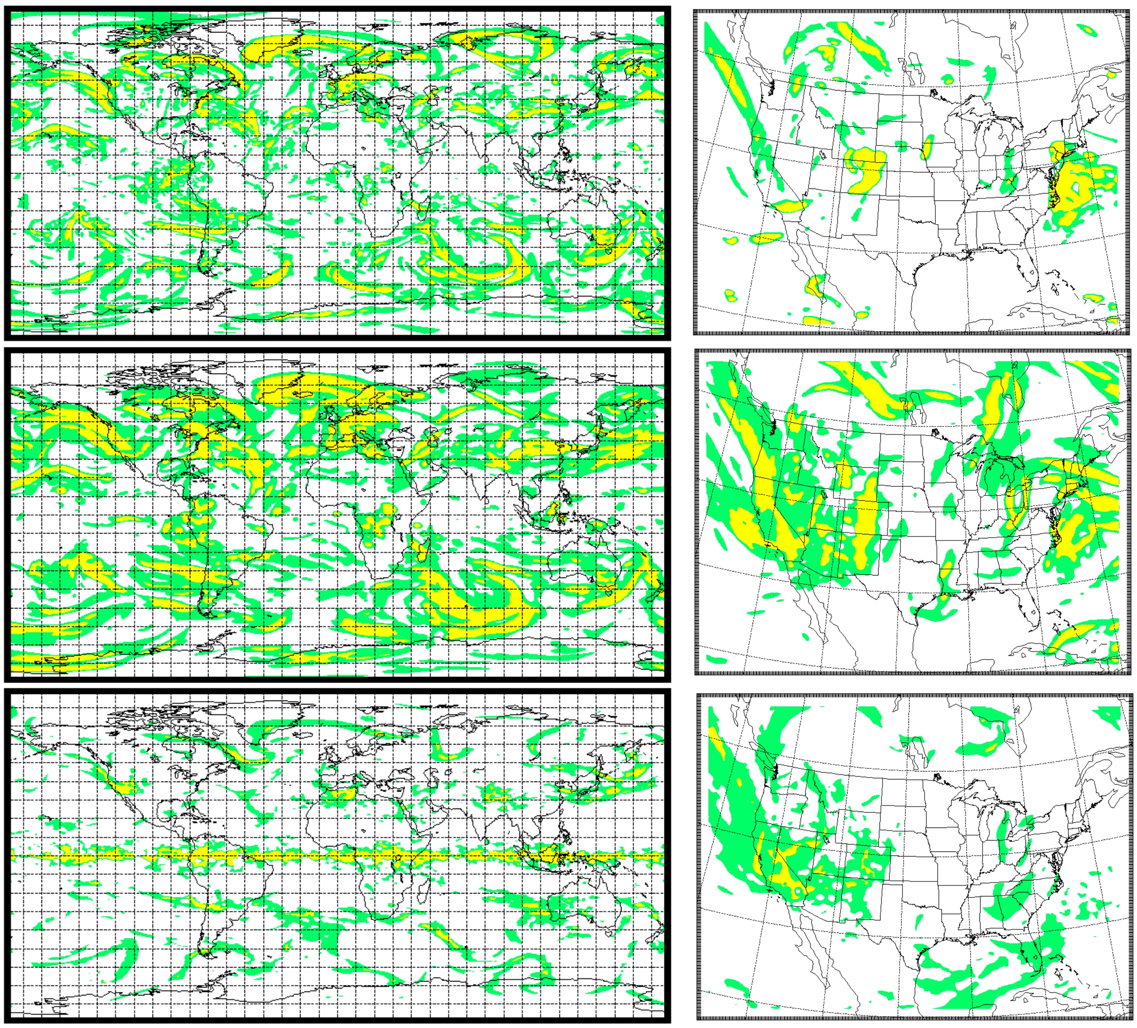


Figure 1: Comparisons between GFS (left column) and RUC (right column) output from three turbulence diagnostics. The top row shows the Ellrod index for a flight level of 35,000 ft., the middle row shows the EDR index at 35,000 ft., and the bottom row shows Richardson number from thermal wind for flight level 20,000 ft.

The following figures show results from the initial GFS GTG combination algorithm, which merges the various individual turbulence indices using global weights to generate global turbulence analyses and forecasts. In the second plot of Figure 2, below, the initial global CDO product (see Task 3) product is overlaid. It appears that, in this case, the GFS model does not capture convectively-induced turbulence (CIT) that is likely associated with some of these storms. This fact underscores the importance of developing CIT diagnostics (Tasks 2 and 4) to augment the model data for producing comprehensive turbulence diagnoses and nowcasts.

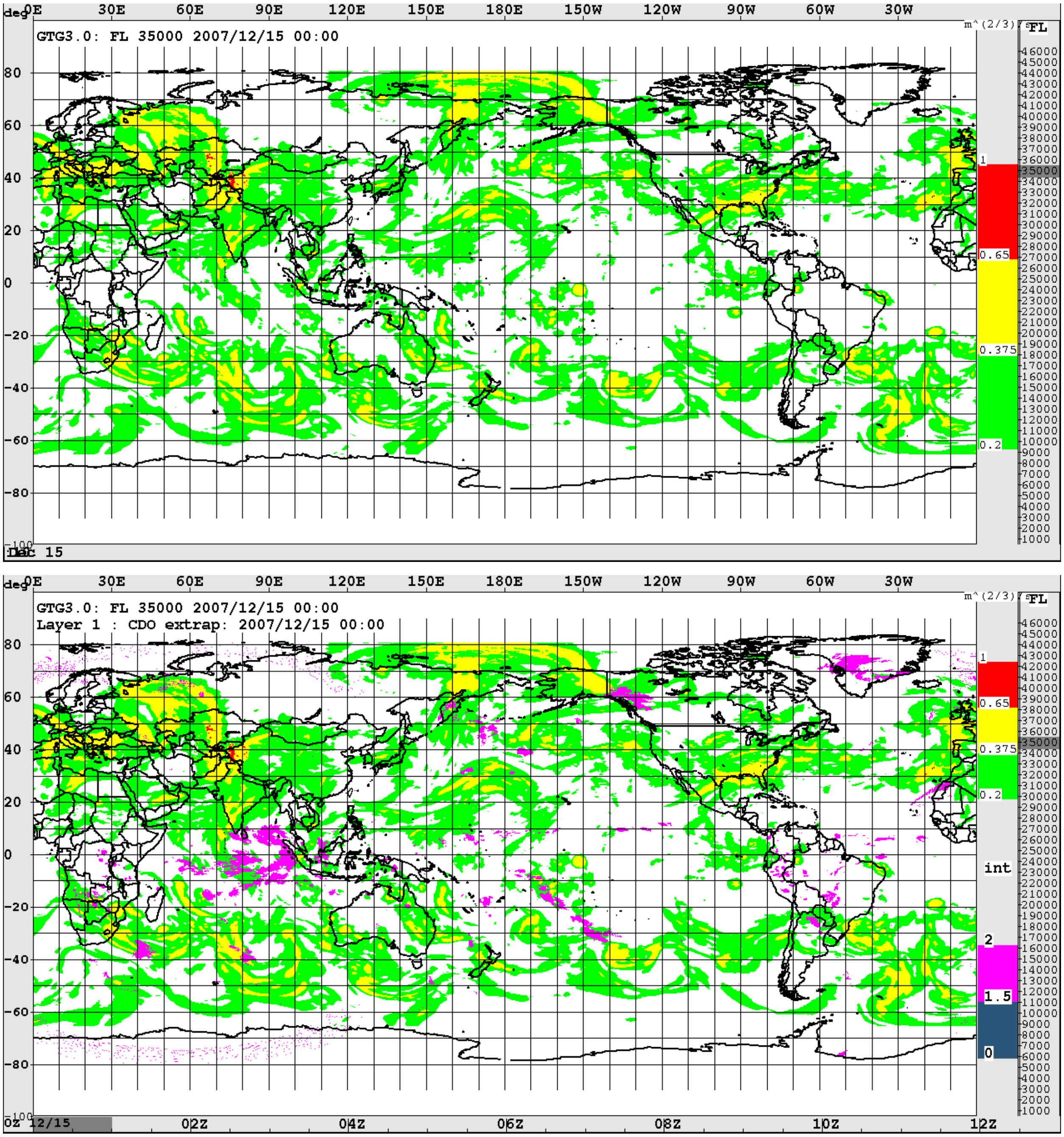
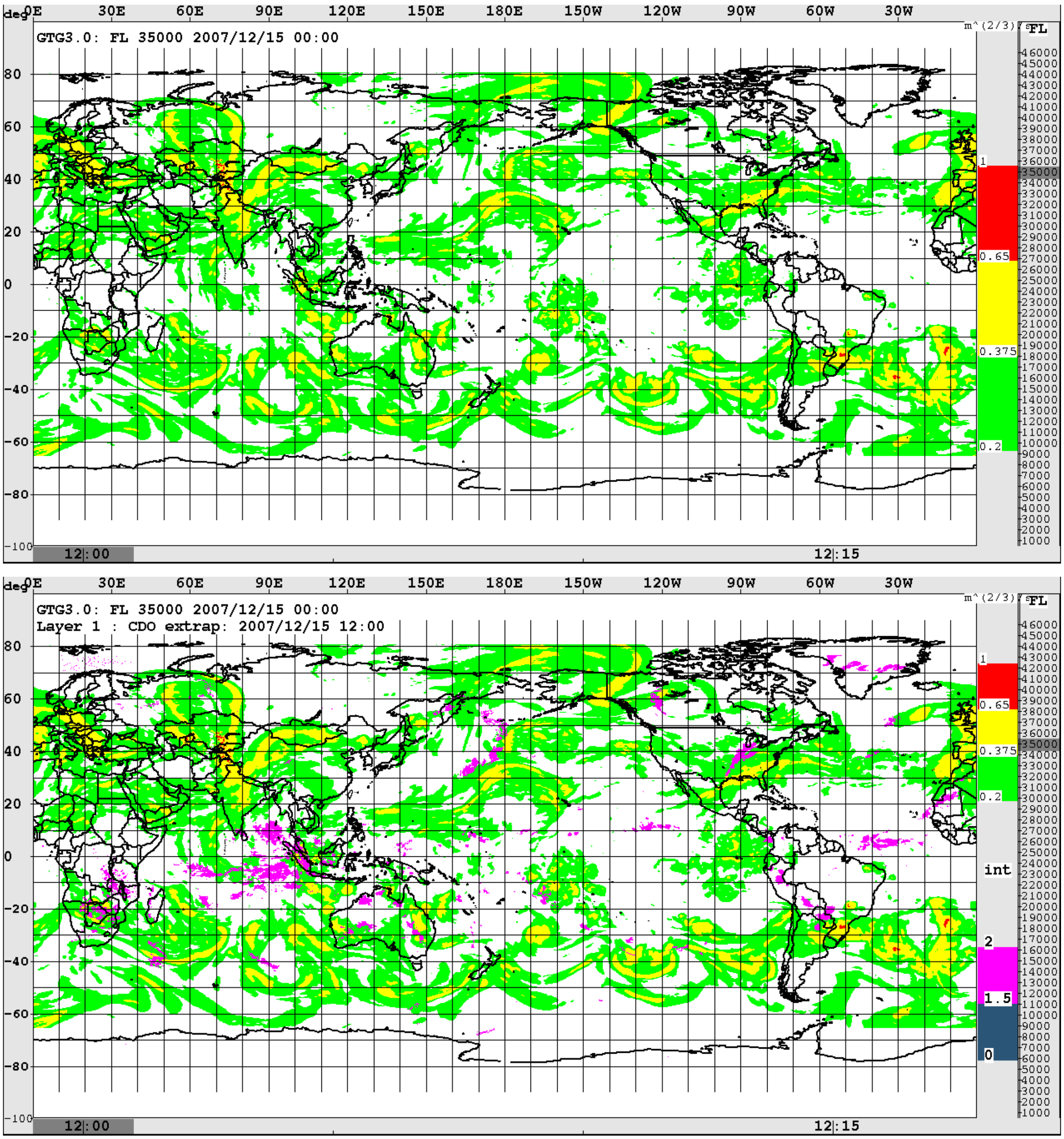


Figure 2: (Top) GFS-GTG 0-hr (analysis) output is shown for 15 December 2007 at 00 UTC at a 35,000 ft flight level. Light turbulence regions are shaded green, moderate turbulence is yellow and severe turbulence is red. (Bottom) The same case but with the global Convective Diagnosis Oceanic (CDO) product overlaid as magenta shapes. The CDO indicates regions of convection that may contribute to producing turbulence (CIT).

The next plots in Figure 3 show similar information except that the 12-hr GFS GTG forecast, valid at 12 UTC on 15 December 2007, is shown. The CDO field is again overlaid, and validation data from pilot reports and aircraft turbulence measurements are also shown. These plots illustrate the global turbulence data visualization capability developed at NCAR and its use in performing data comparisons. Such comparisons will be used to tune the GFS GTG diagnostics, their combination and the integration of satellite and convection turbulence indicators (see Task 5) through both case studies and statistical analyses.



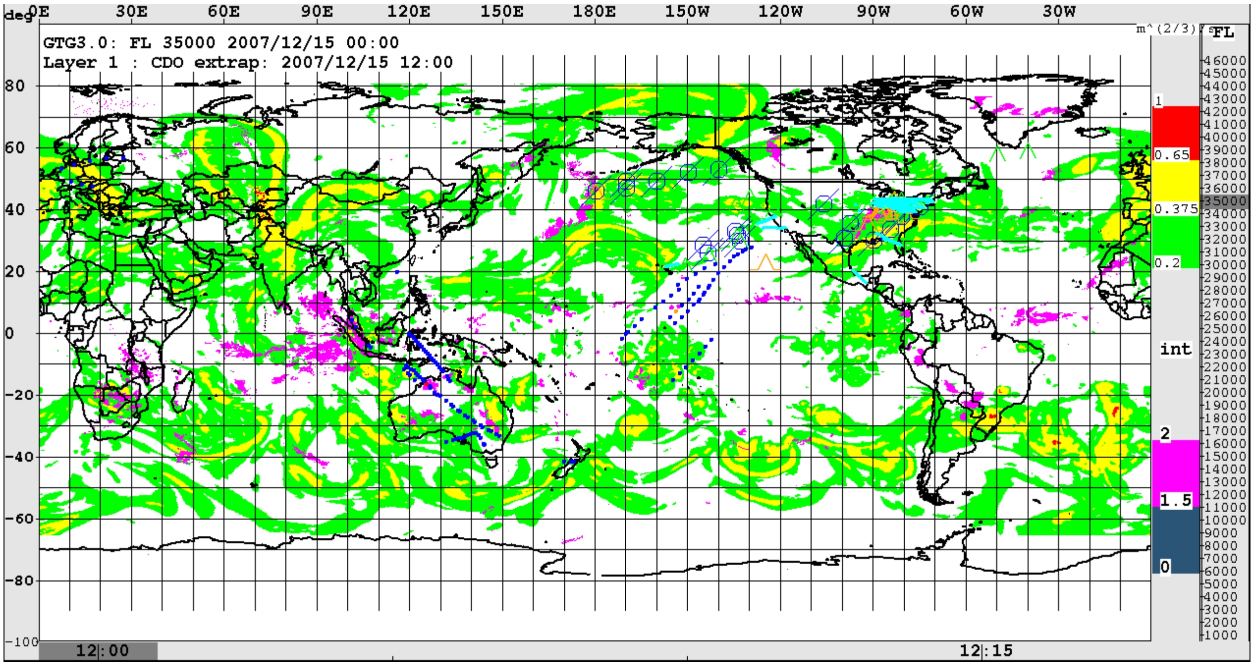


Figure 3: (Top) GFS-GTG 12-hr turbulence forecast output, valid at 15 December 2007 12 UTC, at a 35,000 ft flight level. (Middle) The GFS GTG 12-hr forecast and the CDO (magenta shapes) from the valid time overlaid. (Bottom) GFS GTG 12-hr forecast and the CDO, with overlaid AIREPs and *in situ* turbulence measurement data from Delta, United and Qantas aircraft, valid between 90 minutes before and 90 minutes after the forecast time. AIREPs and *in situ* turbulence data are coded blue for light, orange for moderate and red for severe turbulence.

At the global scale, it is difficult to discern sufficient detail to draw conclusions from these comparisons. For that reason, a higher magnification view of the convective storms south of the Great Lakes region in the continental United States is illustrated in Figure 4 for the GFS GTG 12-hr forecast. These plots show that moderate turbulence was experienced within and near the CDO region. The GFS GTG forecast has some spatial offset towards the southeast but does show that moderate turbulence was forecasted and subsequently observed in the region.

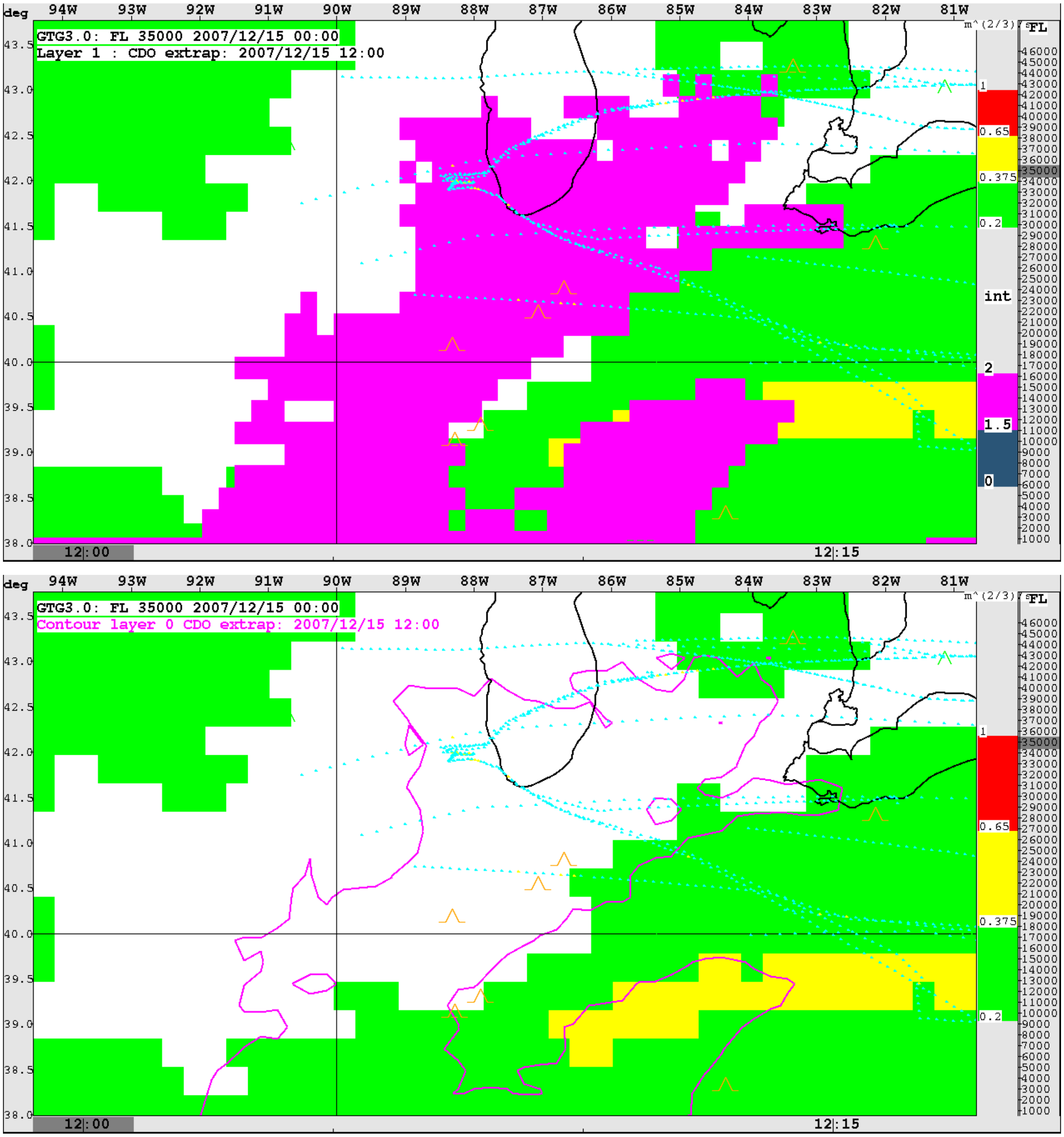
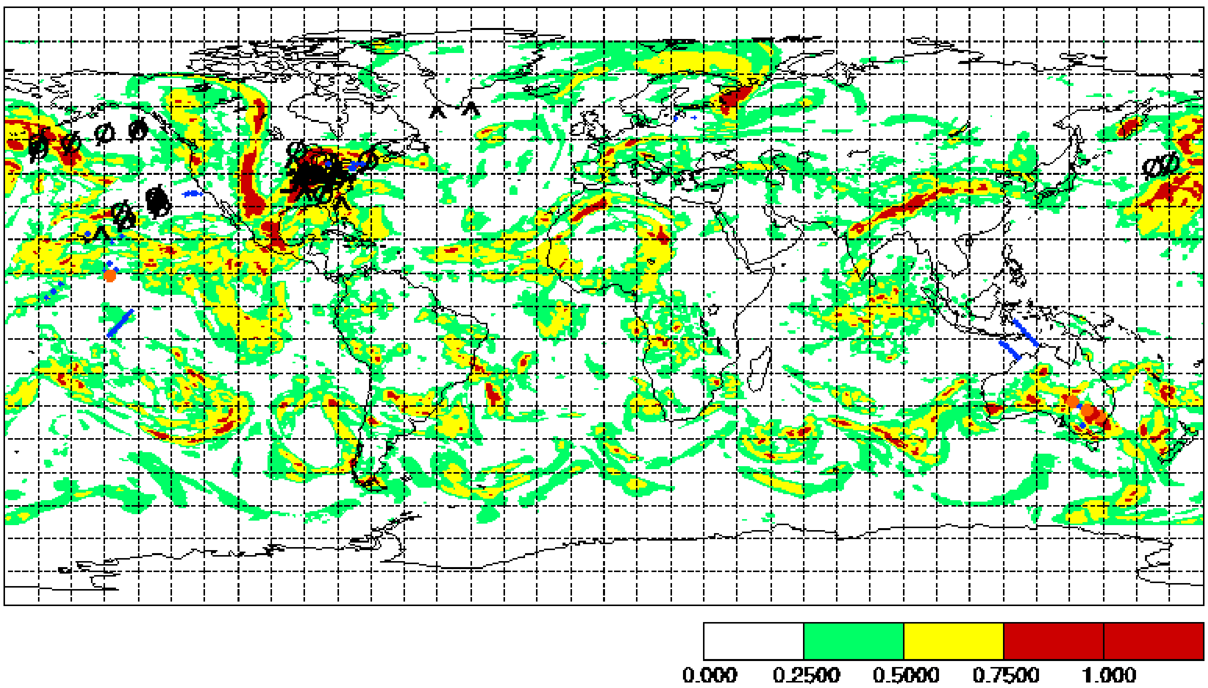


Figure 4: (Top) Magnified view of the region south of the Great Lakes in the CONUS showing the GFS-GTG 12-hr turbulence forecast output, valid at 15 December 2007 12 UTC, at a 35,000 ft flight level with the CDO (magenta shape), turbulence PIREPs (inverted Vs) and *in situ* turbulence data (small dots) overlaid. (Bottom) Same as the top plot except that the CDO output is contoured to allow a better view of the GFS GTG 12 hr forecast grid underneath.

The following three plots in Figure 5 show the output from an experimental probabilistic version of the GFS GTG that makes use of the various model-based diagnostics as members of an ensemble. Shown are probabilities of light-or-greater, moderate-or-greater, and severe-or-greater turbulence, respectively, for the 0-hr analysis valid at 15 December 2007 12 UTC, at a 35,000 ft flight level. Overlaid are turbulence AIREPs and Quantas U_{de} (derived vertical gust) measurements. These measurements do often appear to agree with the GFS GTG analysis, though a statistical comparison will be required to quantify and optimize its skill.



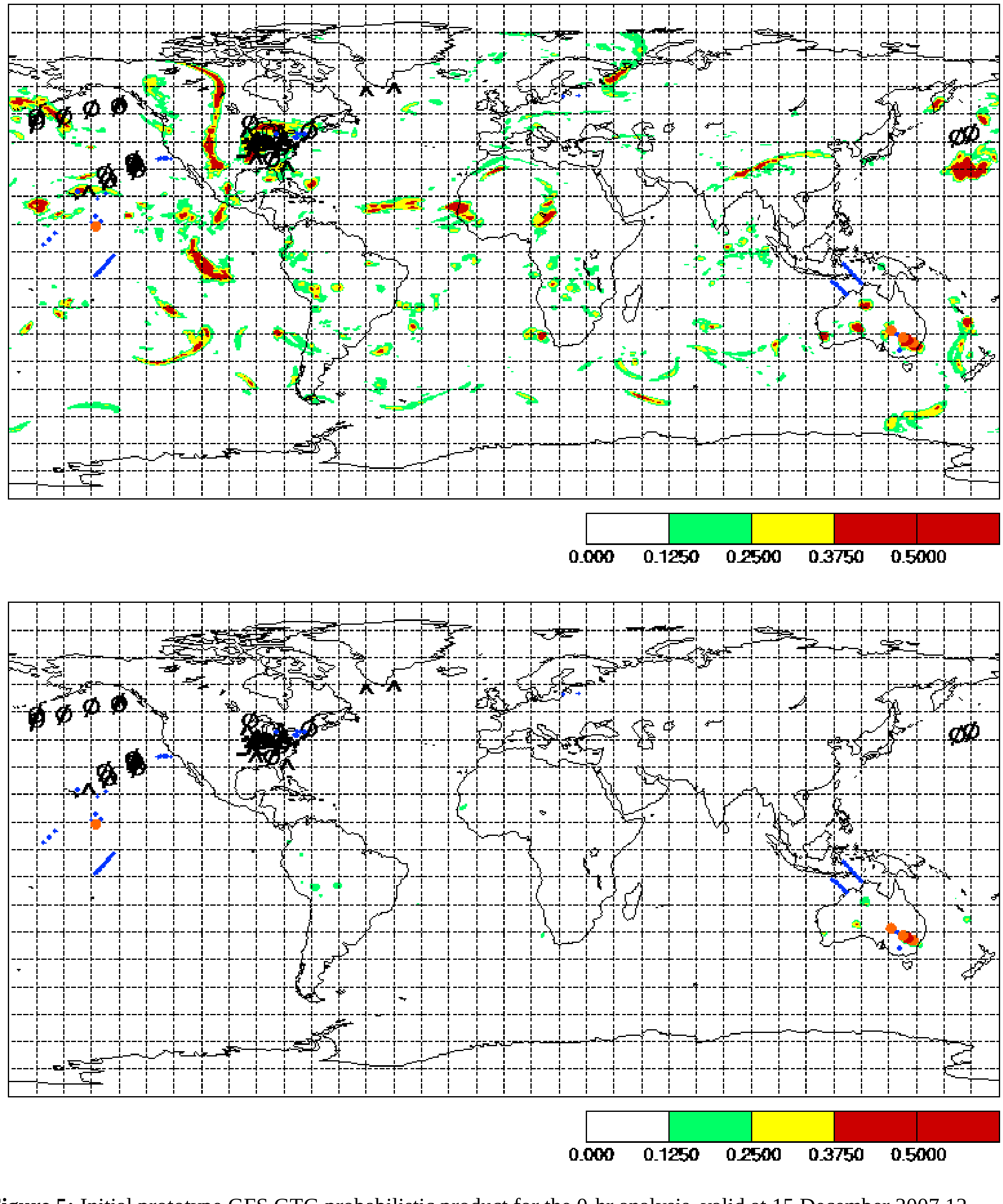


Figure 5: Initial prototype GFS GTG probabilistic product for the 0-hr analysis, valid at 15 December 2007 12 UTC, at a 35,000 ft flight level. (Top) The probability of light or greater turbulence. (Middle) Probability of moderate or greater turbulence. (Bottom) Probability of severe or greater turbulence. Note that the colorscales are different between the light and moderate or severe plots. Overlaid are AIREPs and in-situ measurements from Qantas aircraft.

Appendix B: Further Results from Task 2, Satellite-based Turbulence Identification

This appendix provides results for three major satellite-based turbulence identification efforts. These are the Tropopause Folding Algorithm (TFA), convective overshooting tops (OT) identification, and objective mountain-wave turbulence identification work areas.

Tropopause Folding Algorithm (TFA)

The accuracy of the TFA has been improved by refining the criteria for satellite signatures corresponding to upper-tropospheric turbulence. We now consider gradient feature size, aircraft angle of approach, and distance from the tropopause fold. Also, the algorithm was tested on a 12-month data set of over two million in-situ observations. Further turbulence prediction requirements were refined using model wind data. The algorithm was adjusted to fit more closely with the theory of clear air turbulence due to tropopause folding.

Validation of the tropospheric fold algorithm with United Airlines eddy dissipation rate (EDR) objective turbulence reports over the eastern United States from 01 May 2004 – 30 April 2006 provided by NCAR was accomplished. The validation was based on the TFA running on GOES-12 data, and yielded successful results. Statistical results show that the algorithm achieved a probability of detection of approximately 20% for Light-or-Greater turbulence observations. The algorithm showed a smaller area of 5% detection for the much less frequent Moderate-or-Greater turbulence cases. Also, the algorithm had little skill for the very infrequent Severe-or-Greater cases. The most robust prediction of turbulence occurred in the months of December – February. The high volume of data in the EDR reports enabled a determination of aircrafts' directional sensitivity to turbulence around the jet stream. Examples of the decision support interest field are shown in Figure 6.

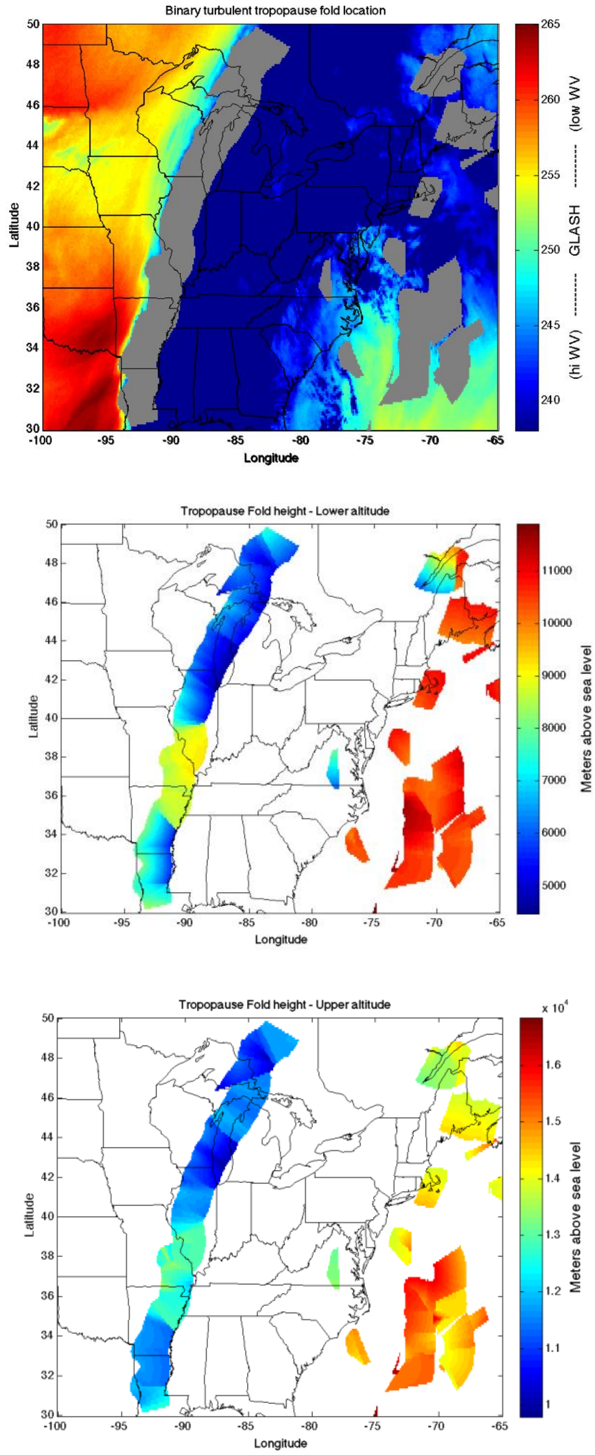


Figure 6: (Top) TFA tropopause fold location detailed in grey. The underlying image is the GOES Layer Average Specific Humidity (GLASH) product, which is an adjustment to the GOES water vapor channel to show specific humidity variations. The lower plots depict an estimate of tropopause fold lower altitude (middle) and upper altitude (bottom) bounds.

Overshooting Tops (OT) Identification

UW-CIMSS has provided to NCAR an objective method for identification of overshooting convective cloud tops. This method utilizes infrared window channel observations from any instrument in LEO or GEO orbit to identify clusters of very cold pixels relative to the surrounding thunderstorm anvil cloud. Comparisons to visible channel imagery, CloudSat and CALIPSO profiles, and synthetic GOES-R ABI imagery shows that the method has good accuracy and offers an improvement over existing overshooting top capabilities described in the literature. Figure 7 shows that, over three convective seasons (2005-2007), aircraft flying very near to overshooting tops experienced turbulence at a higher frequency and stronger intensity than non-overshooting cold cloud pixels. The overshooting top detection software that UW-CIMSS has delivered to NCAR has the capability to process an entire full-disk GOES-12 scan in under 1 minute, providing a valuable turbulence indicator in real-time.

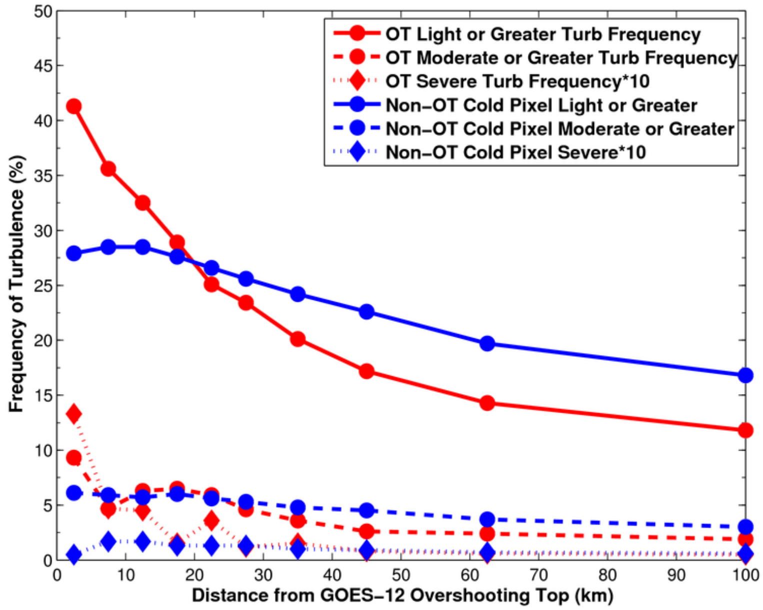
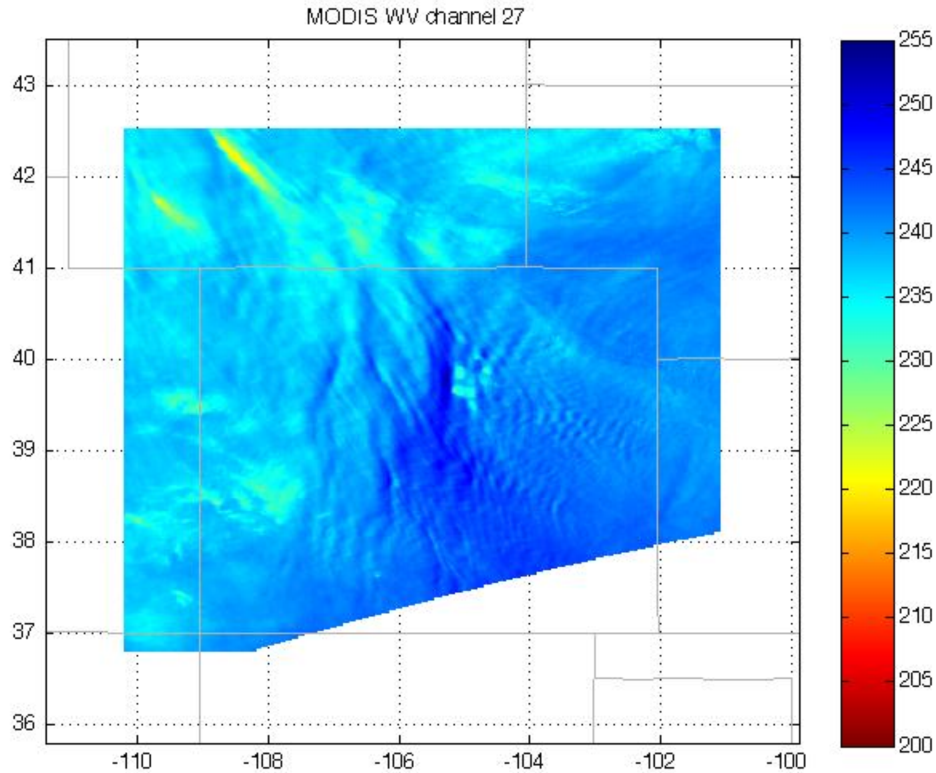


Figure 7: A comparison of overshooting tops detected in GOES-12 imagery and EDR turbulence observations over the 2005-2007 convective seasons (May-September). The frequency of severe turbulence encounters has been multiplied by 10 to better illustrate the difference in frequency between overshooting tops and non-overshooting cold pixels.

Mountain Wave Identification

Mountain waves are responsible for producing significant aviation turbulence over the U.S. An analysis of daily MODIS imagery over the central Rockies from October-April 2005-2006 and 2006-2007 reveals that mountain waves were present in the 6.7 μm water imagery for 68% of all days during these months. CIMSS has analyzed 3.5 years of commercial aircraft eddy dissipation rate (EDR) turbulence observations obtained from NCAR in an effort to better understand the relationship between satellite-observed mountain wave signatures and aviation turbulence. For perspective, moderate or greater intensity turbulence occurred on average for only 0.35% of all EDR observations over the Rocky Mountain Region throughout the duration of this 3.5 year EDR database.

The group at CIMSS is exploring the automated detection of mountain waves through the Morlet wavelet transformation. Figure 8shows an example of the preliminary results from this work.



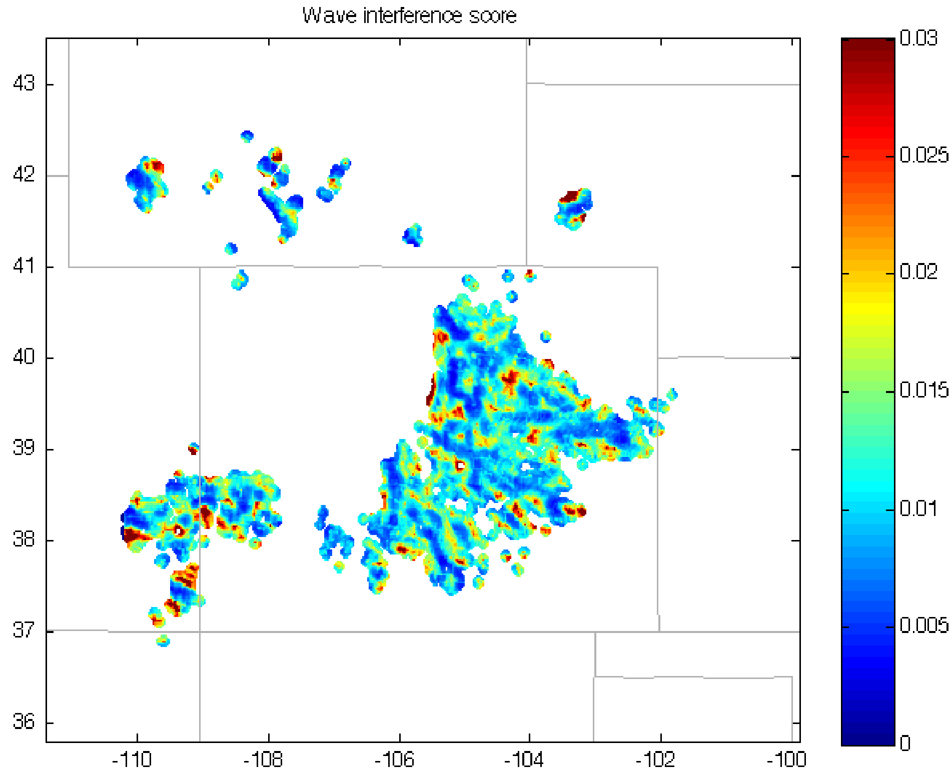
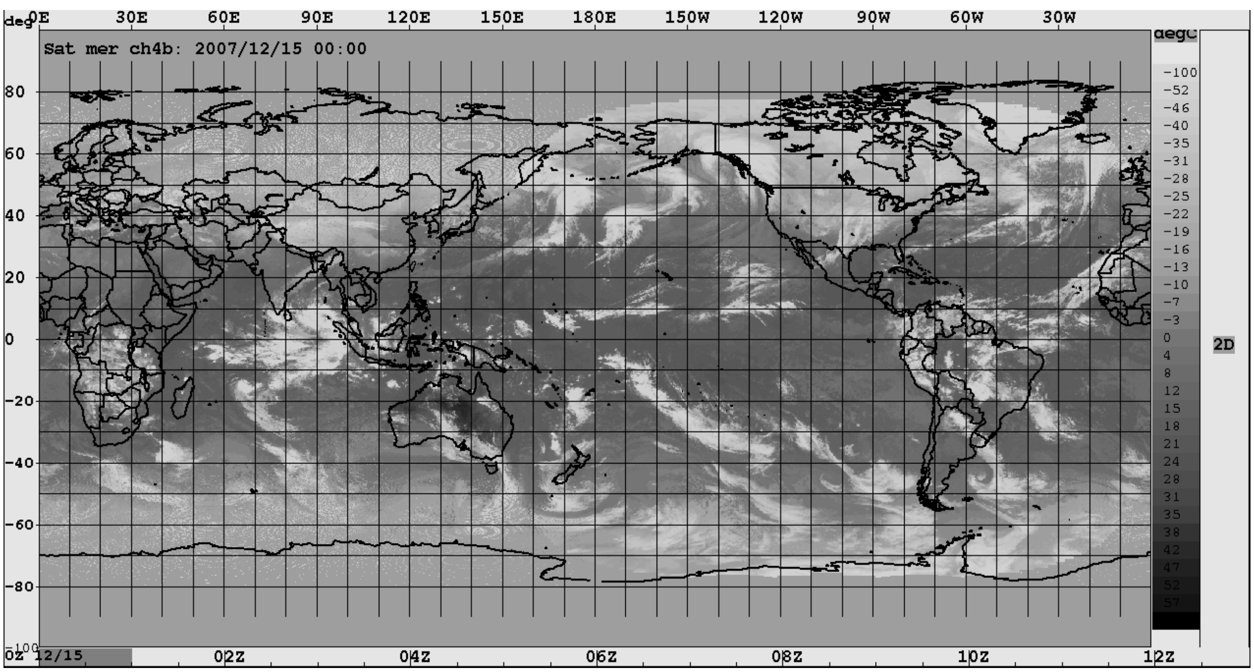


Figure 8: (Top) MODIS 1-km 6.7 um water vapor imagery of a highly turbulent case from 6 March 2004. (Bottom) A new derived quantity called the wave interference scale which provides a normalized score for the combined contribution of wave strength and interference toward turbulence. This product will be validated with EDR data.

Appendix C: Further Results from Task 3, Global Convection Nowcasting

The Convective Diagnosis Oceanic (CDO) is a global convection diagnosis product that has been developed under another NASA grant and is being modified for global use with GOES, Meteosat and MTSAT data. Storms are identified and characterized based on a cloud-top height derived from the satellite longwave infrared data and GFS model temperature profiles. The difference between the satellite-measured longwave and water-vapor channels (the so-called Global Convective Diagnosis, GCD) is used to identify deep convective clouds that have reached the tropopause. The cloud top and GCD are combined to obtain a scalar metric of thunderstorm intensity. NASA TRMM, CloudSat, and CALIPSO data, along with CONUS radar reflectivity and global lightning data will be used to evaluate the convective products' performance. Convection locations and intensity will be used in combination with GFS model fields to diagnose regions of potential CIT (see Task 4).

An example of the global merged longwave IR brightness temperature data and initial global CDO field are shown in Figure 9. See also the CDO overlays with GFS GTG analysis and forecast data in Figure 2, Figure 3, and Figure 4.



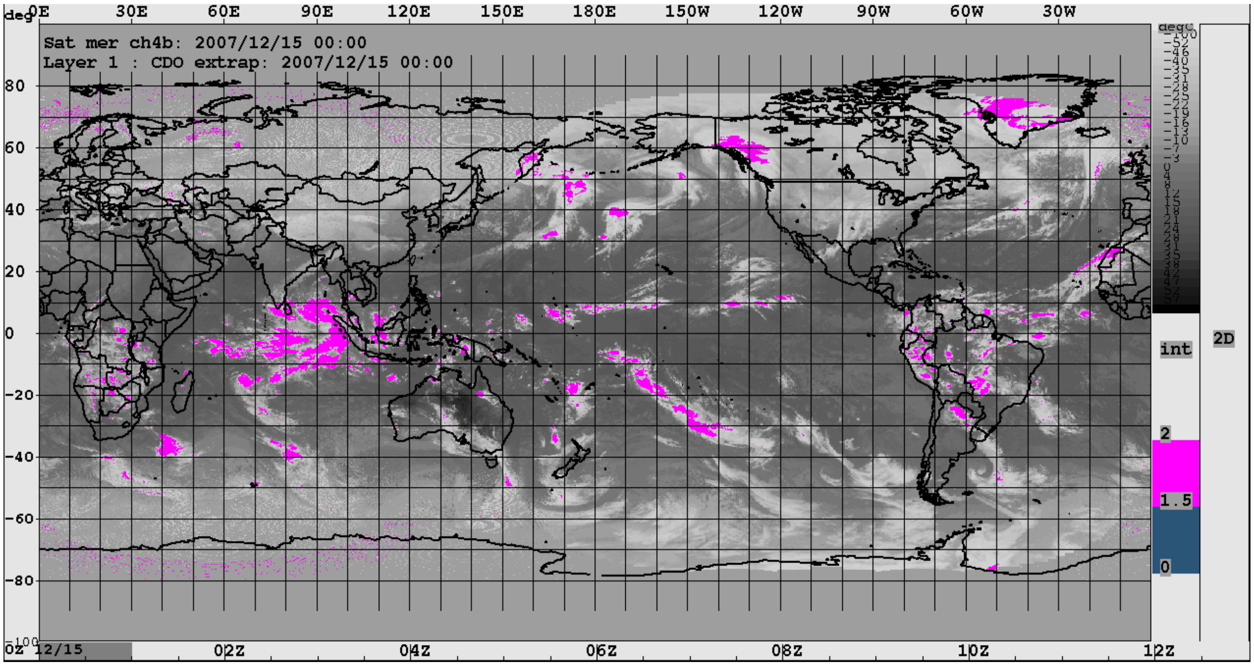


Figure 9: (Top) Longwave brightness temperature data from 00 UTC on 15 December 2007 from GOES, Meteosat, and MTSAT satellites. (Bottom) The same image with CDO regions overlaid in magenta.